ULTRA HIGH ENERGY TAU NEUTRINOS AND FLUORESCENCE DETECTORS: A PHENOMENOLOGICAL APPROACH

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(Dated: February 2, 2008)

Abstract

We investigate the possibility of detecting ultra-high energy cosmic tau-neutrinos by means of a process involving a double extensive air shower, the so-called Double-Bang Phenomenon. In this process a primary tau-neutrino interacts with an atmospheric quark creating a hadronic extensive air shower that contains a tau which subsequently decays creating a second extensive air shower. The number of these events strongly depends on the cross section and on the flux of ultra-high energy tau-neutrinos arriving at the Earth's atmosphere. We estimate the potential of optical detectors to observe Double-Bang events induced by tau-neutrinos with energies of about 1 EeV whose detection may confirm the maximal mixing observed in the atmospheric neutrinos also for ultra-high energy neutrinos, and give information on the neutrino flux and cross-section. For neutrino-nucleon Standard Model extrapolated cross-section and thick source model of flux (MPR), we estimate an event rate of 0.48 yr^{-1} for an observatory with two fluorescence detectors with 90% efficiency in the neutrino energy range $0.5 < E_\nu < 5$ EeV.

PACS numbers: 13.15.+g, 96.40.Pq

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I. INTRODUCTION

It is believed that ultra-high energy (UHE) cosmic neutrinos may play an important role to explain the origin of cosmic rays with energies beyond the GZK limit of few times 10^{19} eV [1, 2], once that neutrinos hardly interact with cosmic microwave background or intergalactic magnetic fields, keeping therefore its original energy and direction of propagation. Even if they have masses or magnetic moments, or travel distances of the order of the visible universe, those characteristics do not change very much. Possible sources of these UHE neutrinos, like Active Galactic Nuclei and Gamma Ray Bursts, are typically located at thousands of Mpc [3, 4].

Considering that neutrinos come from pions produced via the process $\gamma + p \to N + \pi$ [4], that there is an additional ν_e flux due to escaping neutrons and that about 10% of the neutrino flux is due to proton-proton (pp) interactions, the proportionality of different neutrino flavors result: $\nu_e : \nu_\mu : \nu_\tau = 0.6 : 1.0 :< 0.01$ [5]. Nevertheless, observations of solar [6] and atmospheric [7] neutrinos present compelling evidence of neutrino flavor oscillations. Such oscillations have been independently confirmed by terrestrial experiments. KamLAND [8] observed $\bar{\nu}_e$ disappearance confirming (assuming CPT invariance) what has been seen in solar neutrino detections and K2K [9, 10] observed $\nu_\mu/\bar{\nu}_\mu$ conversion compatible with what has been detected in atmospheric neutrino observations.

In order to understand these experimental results by means of neutrino oscillations, two scales of mass squared differences and large mixing angles have to be invoked. For solar and KamLAND observations, $\Delta m^2_\odot \sim 7 \times 10^{-5}$ eV^2 and $\sin^2 2\theta_\odot \sim 0.8$. And for atmospheric neutrino and K2K, $|\Delta m^2_{atm}| \sim 3 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{atm} \sim 1$. Moreover LSND experiment [11] may have observed $\bar{\nu}_\mu \to \bar{\nu}_e$ transition which can be also explained by neutrino oscillations with a large mass scale, $|\Delta m^2_{LSND}| \sim (0.5 - 2.0)$ eV^2. Such results will soon be checked by MiniBooNE [12]. These scales require four neutrino oscillation framework (or three, if LSND results will not be confirmed by MiniBooNE experiment) which imply, for UHE's of the order 1 EeV or higher, oscillation lengths much smaller than typical distances from the sources of UHE neutrinos. Consequently when neutrino flavor oscillations are taken into consideration the flavor proportion will be modified to $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$. Therefore one expects a considerable number of ν_τ arriving at the Earth.

In this paper we investigate the possibility of detecting UHE cosmic ν_τ by means of a

process in which a double Extensive Air Shower (EAS) is identified, the so-called Double-Bang (DB) Phenomenon. In that kind of event a ν_τ interact with a quark via charged current creating one cascade of hadronic particles and a tau lepton which subsequently decays producing a second cascade. DB Phenomenon was first proposed for detectors where the neutrino energy should be around 1 PeV [5]. It does not happen with neutrinos different from ν_τ. The electron generated by an ν_e interacts immediately after being created and the muon generated by a ν_μ, on the other hand, travel a much longer distance than the size of the detector before interacting or even decaying. For energies of the order of 1 EeV, where the radiative processes become more important than ionization, the total energy loss in the atmosphere is not important once that for those high energies, crossing 36000 g/cm^2 in iron, we estimate, by extrapolation, that the muon will loose about 36% of its initial energy [13]. So we may not have DB events from them.

In order to identify a DB Phenomenon in the atmosphere, an optical detector must be used to probe the longitudinal development of EAS's, recording the fluorescence light emitted by the excited nitrogen molecules of the Earth's atmosphere when the EAS passes through it. One has to look for two EAS's coming from the same direction inside the field of view (f.o.v.) of the detector, i.e., in the physical space around the detector in which an event can be triggered. Based on the phenomenology of the process we conclude that the features of optical detectors like the Fluorescence Detectors (FD's) used by the Pierre Auger Observatory [14] favor the observation of DB events with ν_τ energies around 3 EeV. The estimated number of DB events observed in these FD's varies from hundreds in a year to few events in hundreds of years depending mainly on the primary ν_τ flux and cross section.

As we made the calculation based most on phenomenological aspects, the conclusion of this work is not dependent on numerical simulations. To have accurate conclusion based on simulations, first one needs to improve the simulation programs including tau and ν_τ interactions with particles in the atmosphere. There are some works that study the differences between the longitudinal development of EAS's generated by protons, heavier nuclei and different neutrino flavors [15, 16]. In reference [16] the authors use CORSIKA+Herwig Monte Carlo simulations to have ν_e and ν_μ as primary particles, that will not produce DB's.

This paper is organized in the following way: Section II has a brief introduction to the DB Phenomenon. Section III describes how we calculate the DB event rate for a Pierre Auger-like FD and for a configuration with 2 FD's and 90% efficiency for neutrino energy between

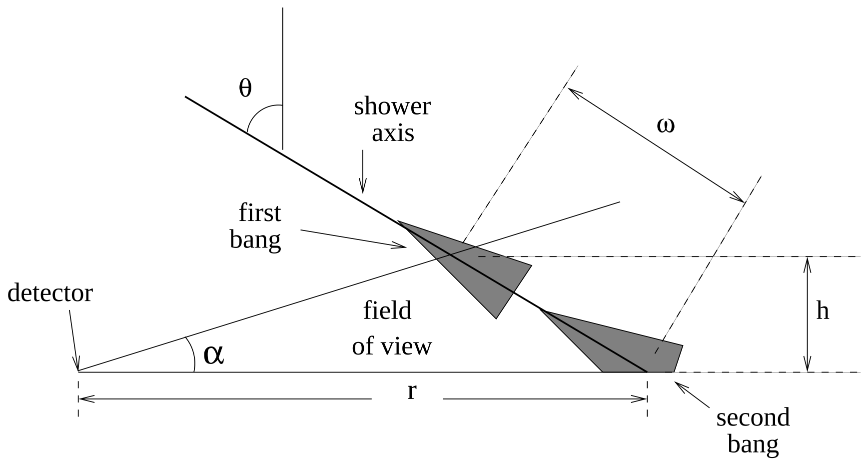

FIG. 1: A schematic view of a Double-Bang and the f.o.v. of the Fluorescence Detector. See text in Section II for details.

0.5 and 5 EeV. Section IV contains the number of events calculated for different models and limits of UHE neutrino flux and discuss how could we take some physical information from the two different efficiency approaches described in Section III. Section V concerns possible background events and the conclusions are in Section VI.

II. THE ULTRA-HIGH ENERGY DOUBLE-BANG

Studying the characteristics of FD's, such as its efficiency and f.o.v. and the characteristics of the DB events generated by UHE ν_τ, one can estimate the rate of this kind of event expected in that kind of detector.

Fig. 1 shows a schematic view of an UHE DB with the detector position and the time integrated development of the two EAS's, one created by the UHE ν_τ interacting with a nucleon in the atmosphere and the other created by the decay of the tau generated in the first interaction of the ν_τ. The f.o.v. of the Pierre Auger Observatory FD, for example, will be comprehended between angles near the horizontal ($\alpha \sim 2^o$) and $\alpha \sim 30^o$, and a maximum radius r of approximately 30 km. The approximate maximal height from where the DB can be triggered by the FD is h and ω is its projection in the DB propagation axis. The zenith angle is represented by θ.

The total amount of light emitted by the first EAS is related to the energy transfered to the quark at the moment of the first ν_τ interaction, which we define as E_1. The neutrino

energy E_ν is the sum of the tau energy E_τ and E_1, i. e., $E_\nu = E_1 + E_\tau$. For charged current interactions above 0.1 EeV, approximately 20% of the neutrino energy is transfered to the quark [17] and in our calculations we considered it constant. The second EAS, resulting from the tau decay, carries an energy E_2 of approximately 2/3 E_τ and may be specially visible when the tau decay is hadronic, which happens with a branching ratio of around 63% [18].

Therefore, very roughly, we have $\langle E_1 \rangle \sim 1/5 E_\nu$ and $\langle E_2 \rangle \sim 2/3 \langle E_\tau \rangle \approx 8/15 E_\nu$ and the relation between E_1 and E_2 is given by: $E_2/E_1 \sim \frac{8}{15} E_\nu / \frac{1}{5} E_\nu \approx 2.67$. The distance traveled by the tau before decaying in laboratory frame is $L = \gamma c t_\tau$, where $\gamma = E_\tau/m_\tau$ and t_τ is the tau mean life time, that has an error of approximately 0.4% [18]. When the tau energy is given in units of EeV, $L \simeq \frac{E_\tau}{[\mathrm{EeV}]} \times 49$ km $\simeq \frac{E_\nu}{[\mathrm{EeV}]} \times 39.2$ km.

Now we compare the tau decay length with its attenuation length in the Earth's atmosphere. The energy loss had been calculated [19] including bremsstrahlung, e^+e^- par production and deep inelastic scattering based on a model of the form $-dE/dx = a + b(E)E$ where a is the ionization energy loss and b is the sum of the other contributions due to radiative processes. The second term, b, is dominant above a few 100 GeV. So we obtain an attenuation length for the tau in the atmosphere $L_a = (\rho \sum b)^{-1} \simeq 33600$ km for $b = 0.08 \times 10^{-7}$, 1.4×10^{-7} and $1.0 \times 10^{-7}\mathrm{g}^{-1}\mathrm{cm}^2$ from bremsstrahlung, par production and deep inelastic scattering contributions respectively and $\rho = 1.2 \times 10^{-3}\mathrm{g\ cm}^{-3}$. The attenuation length (L_a) is much longer than the decay length (L) and so we did not consider energy loss for the tau propagation.

III. EVENT RATE

To calculate the possible number of events in a FD, consider for simplicity one Pierre Auger-like FD with a f.o.v. of 360^o. Then we can write the equation for the DB event rate:

$$\frac{dN_{events}}{dt} = \int_{E_{th}}^{\infty} dE_\nu\ \Phi_\nu(E_\nu)\ \mathcal{A}(E_\nu, r, \theta) \tag{1}$$

where, E_{th} is the minimum detectable energy according to the efficiency of the FD, E_ν is the ν_τ energy, Φ_ν is the flux of UHE ν_τ at the Earth depending on the model of the extra galactic source of high-energy cosmic rays considering maximal mixing and

$$\mathcal{A}(E_\nu, r, \theta) = \int_{\Omega, A} d\Omega\ dA\ P_{int}(E_\nu, \theta)\ F_{trig}(E_\tau, r, \theta)\ \Sigma(E_1, r) \tag{2}$$

is the acceptance. Ω and A are the solid angle covered by the detector and the area under the f.o.v. of the detector respectively. $P_{int}(E_\nu, \theta)$ is the probability of the ν_τ to interact in a given point of the atmosphere, $F_{trig}(E_\tau, r, \theta)$ is a factor that indicates how probable is to trigger a DB sign and $\Sigma(E_1, r)$ is the efficiency of the FD. In the following subsections we explain each term accurately.

A. Interaction Probability

The interaction probability is given approximately by:

$$P_{int}(E_\nu, \theta) = \sigma_{CC}^{\nu N}(E_\nu)\ N_T(\chi) \tag{3}$$

where $\sigma_{CC}^{\nu N}(E_\nu)$ is the average charged current cross section of the neutrino-nucleon interaction and $N_T(\chi)$, the average total number of nucleons per squared centimeter at the interaction point in the atmosphere. $N_T(\chi) = 2N_A\chi(\theta)$, where N_A is the Avogadro's number and $\chi(\theta)$ is the slant depth of the atmosphere within the points where the neutrino must interact to generate a DB event inside the f.o.v. of the FD.

Considering the Earth's curvature, the atmospheric slant depth can be approximately written as:

$$\chi(\theta, l) = \int_\lambda \rho(H = l\cos\theta + \frac{(l\sin\theta)^2}{2R})d\lambda \tag{4}$$

where λ is the path along the arrival direction from the source until the interaction point in the atmosphere, ρ is the atmospheric density, H the vertical height, l is the distance between the interaction point and the point toward the particle goes through on Earth (the slant height), and θ, the zenith angle. The atmospheric depth as a function of the zenith angle is shown in Fig. 2 where we can see that the probability for a neutrino to interact giving raise to a vertical EAS is very low because the atmospheric depth is about 1000 g/cm^2, approximately 36 times less than the atmospheric slant depth in the horizontal case.

Taking the tau decay length $L(E_\tau) = 40$ km, for $E_\nu = 1$ EeV, plus a distance of 10 km for the second EAS to reach its maximum in the case of a horizontal EAS [19], we calculated the first interaction occur approximately 50 km faraway from the detector. In this case may be difficult to detect the maximum of the first EAS because it will probably develop before reaching the f.o.v. of the FD. We also estimate that if the first interaction happens about 30 km faraway from the detector, the maximum of the first EAS can be seen, but in

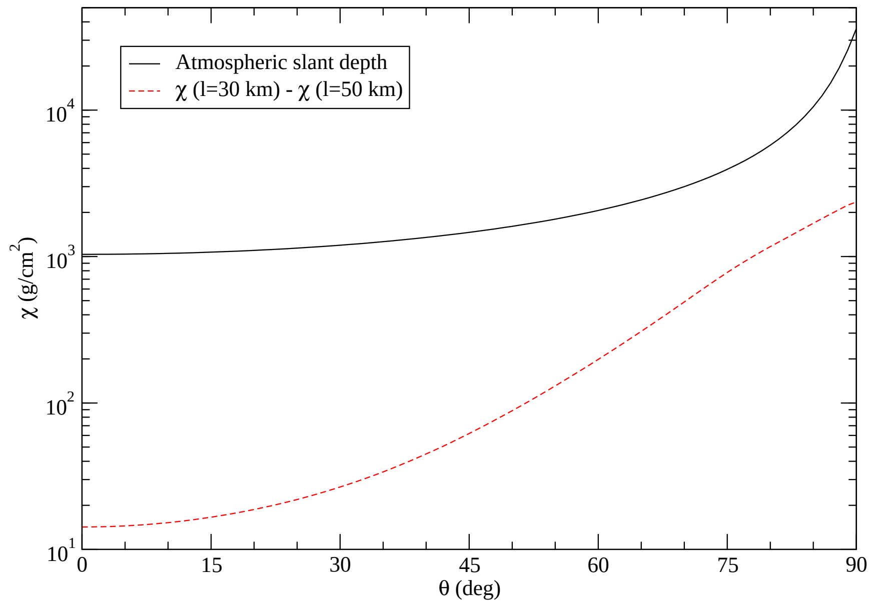

FIG. 2: Atmospheric slant depth and total depth within the region where UHE ν_τ's have to interact to generate DB's, as a function of the zenith angle.

the other hand may be difficult to detect the maximum of the second EAS that probably will reach the ground before its maximum development. To calculate the number of events presented in Section IV we considered the first interaction have to occur in a point within 50 km and 30 km faraway from the detector.

The interaction probability is calculated with $\chi(\theta)$ given by:

$$\chi(\theta) = \int_{l_i}^{l_f} \frac{\partial \chi(\theta, l)}{\partial l} dl = \chi(\theta, l_f = 30 \text{ km}) - \chi(\theta, l_i = 50 \text{ km}) \tag{5}$$

As the cross section of UHE neutrinos is unknown, usually one adopts the extrapolation of parton distribution functions and Standard Model (SM) parameters far beyond the reach of experimental data. In this way, one can estimate a value for the cross section of the neutrino-nucleon interaction of about 10^{-32} cm^2, for energies around 1 EeV. Some authors say that this extrapolation gives a neutrino-nucleon cross section that is too high [20] but others use models that increase this same cross section to typical hadronic cross section values [15]. In this work we use the following cross section parametrization:

$$\sigma_{CC}^{\nu N} = (5.53 + 5.52) \times 10^{-36} \left(\frac{E_\nu}{[\text{GeV}]} \right)^{0.363} \text{cm}^2 \tag{6}$$

which is the SM extrapolation for the neutrinos plus anti-neutrinos and nuclei cross section in charged current interactions , which have 10% accuracy within the energy range $10^{-2} < E(\mathrm{EeV}) < 10^3$ when compared with the results of the CTEQ4-DIS parton distributions [21].

B. Trigger Factor

We define the trigger factor as given by:

$$F_{trig}(E_\tau, r, \theta) = P_{had}\ P_L\ \frac{\omega(r,\theta)}{L(E_\tau)} \tag{7}$$

where, P_{had} is the hadronic branching ratio of tau decay ($P_{had} \simeq 0.63$ [18]), P_L is the mean percent amount of taus that decay within the distance $L(E_\tau)$ ($P_L \simeq 0.63$), $L(E_\tau)$ is the distance traveled by the tau in laboratory frame and $\omega(r,\theta)$, as can be seen in Fig. 1, is the approximate size of the shower axis inside the f.o.v. of the detector where the vertical plane containing the shower axis passes through the center of the FD. In Eq. 7, we are imposing $\omega(r,\theta)/L(E_\tau) = 1$ if $\omega(r,\theta) > L(E_\tau)$ so that we have a conservative estimation of the trigger factor. We considered only showers moving away from the detector since, in the opposite case, a large amount of Čerenkov light arrives together with the fluorescence light, spoiling a precise data analysis [22].

C. Efficiency

The efficiency of the FD was estimated as:

$$\Sigma(E_1, r) = \Upsilon\ \Sigma'(E_1)\ \Sigma''(r) \tag{8}$$

where, Υ is the fraction of the time the fluorescence detector will work ($\Upsilon \simeq 0.1$ because the fluorescence detector can only operate in clear moonless nights), $\Sigma'(E_1)$ is the efficiency depending on the energy of the first EAS of the DB Phenomenon that is less energetic than the second one and $\Sigma''(r)$ is the efficiency depending on the distance from the EAS core, where it reaches the ground, to the FD. $\Sigma'(E_1)$ and $\Sigma''(r)$ depend on the characteristics of each detector. For $\Sigma''(r)$ we used a Gaussian distribution centered at $r = 12.5$ km faraway from the detector and variance of 5.0 km. The behavior of $\Sigma''(r)$ can be seen in Fig. 3. We analyze two $\Sigma'(E_1)$ cases. For the first case we considered $\Sigma'(E_1)$ rising logarithmically from

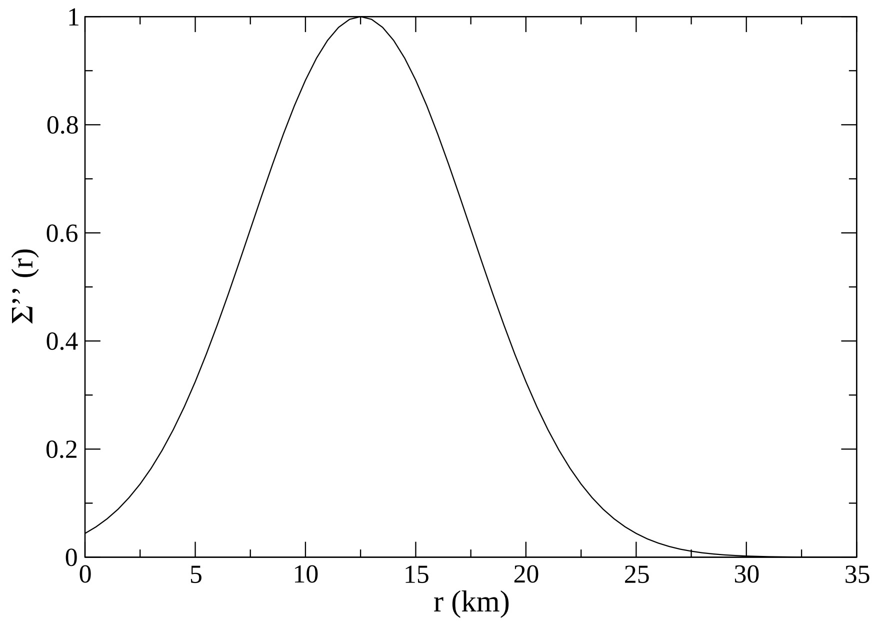

FIG. 3: Efficiency as a function of the distance from the center of the detector.

0 to 1 in the energy range between approximately 0.3 EeV $< E_1 <$ 30 EeV. This value may be coherent with the characteristics of a Pierre Auger-like FD. In the second case we considered 90% efficiency ($\Sigma'(E_1) = 0.9$) for neutrino energies between 0.5 and 5 EeV. The behavior of both $\Sigma'(E_1)$ can be seen in Fig. 4, in terms of E_ν.

IV. RESULTS

Using Eq. 1 with all the phenomenological considerations given above, we calculated the expected DB event rate which can be seen in Table I for different models and limits of UHE cosmic ray flux and in different energy intervals. The last column of Table I shows the event rate in an hypothetical case with 90% efficiency in the more relevant energy range for DB events (0.5 EeV $< E_\nu <$ 5 EeV), using 2 FD's with $\alpha = 60^o$ (see Fig. 1).

From Table I and Fig. 5 one can learn which is the energy interval which is relevant to detect DB events with a Pierre Auger-like FD. The models WB [26] and MPR [27] are limits for the UHE neutrino flux based on cosmic ray observations. Both consider the neutrinos coming from the interactions of protons and photons in the sources generating pions that will decay into muons, electrons and neutrinos. The basic difference is that the authors in WB state that the sources are completely transparent to the protons and in the other hand

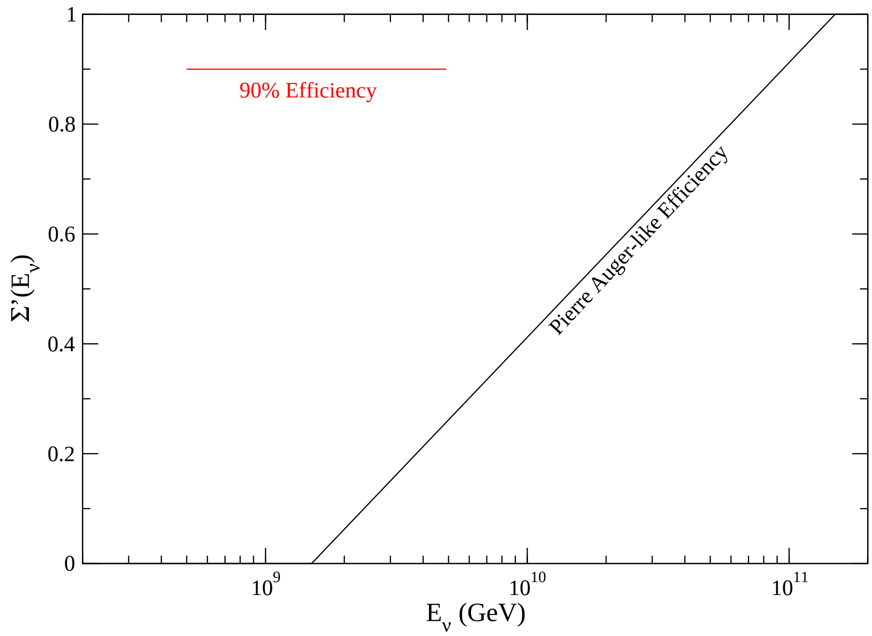

FIG. 4: Efficiency as a function of the neutrino energy. The Pierre Auger-like efficiency was used to calculate the event rate showed in columns N_1, N_2 and N_3 of Table I, and the 90% efficiency was used to calculate the number of events for two FD's with 60^o f.o.v. showed in the last column of Table I.

MPR say that the sources may have some opacity to the protons that generate neutrinos in the interactions with the ambient light in the source. So there could be some neutrino flux that arrive at the earth but it might not be associated with the cosmic ray flux observations. A reasonable flux model might predict an event rate between these two limits.

Fig. 6 shows the dependence of the acceptance with the zenith angle. The acceptance is higher for events coming from almost horizontal angles, but it is significant even for angles around 60 degrees.

Concerning the longitudinal development of the DB as a function of the incident angle and energy of the primary neutrino, the convolution of the terms $F_{trig}(E_\tau, r, \theta)$ and $\Sigma(E_1, r)$ restricts the energies observed. For relatively low energies ($E_1 < 0.3$ EeV) the efficiency $\Sigma'(E_1)$ of the detector will be low and for relatively high energies the factor $F_{trig}(E_\tau, r, \theta)$ may be too small because $L(E_\tau)$ in Eq. 7 will be too large. In the hypothetical case of 90% efficiency for energies between 0.5 and 5 EeV and two FD's with $\alpha = 60^o$, a significant number of events can be measured.

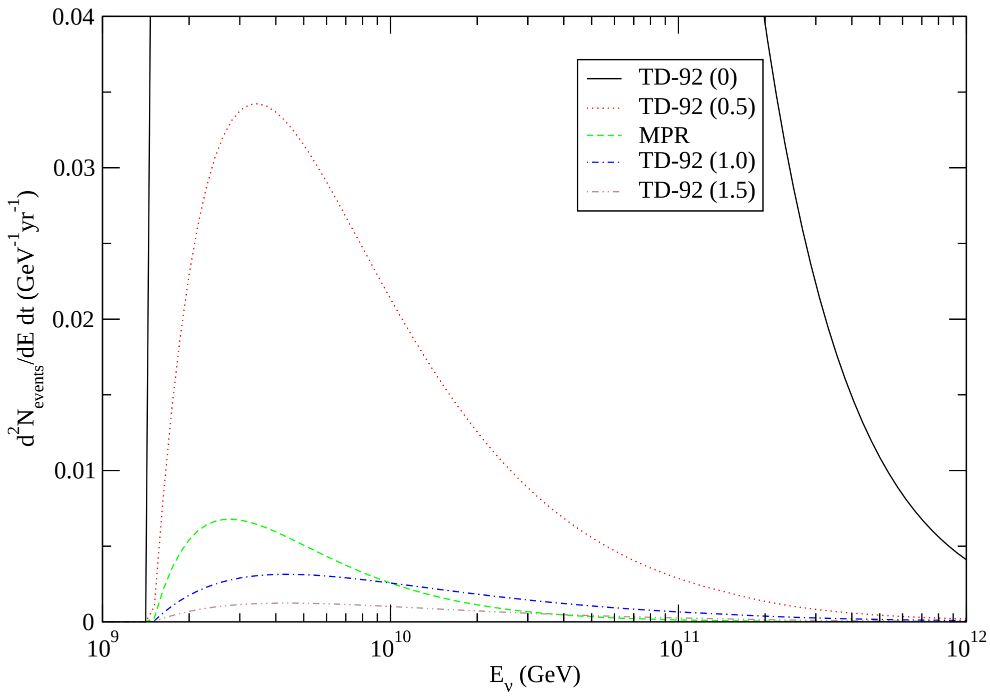

FIG. 5: Differential event rate for a Pierre Auger like FD for different models of cosmic ray flux.

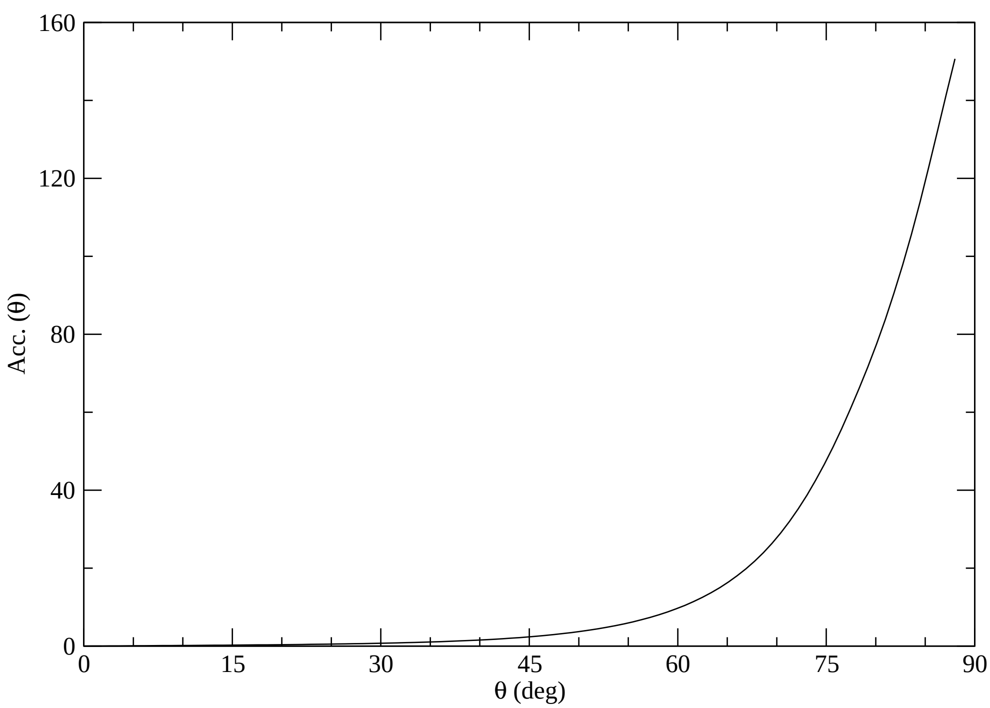

FIG. 6: Dependence of the acceptance with the zenith angle.

TABLE I: Number of events in the Pierre Auger-like FD during a period of one year, calculated in different regions of the energy spectrum and for different models and limits of cosmic ray flux. The last column was calculated with different considerations on the FD characteristics. See text for details. TD-92 stands for the model in reference [23]; TD-96 for the model in reference [24]; AGN-95J for the model in [25]; WB for [26] and MPR for [27].

Models	$N_1{}^a$	$N_2{}^b$	$N_3{}^c$	$N_4{}^d$
TD-92(0)	1.83	0.46	0.03	118
TD-92(0.5)	0.03	0.01	0.001	1.46
MPR	0.005	9.0×10^{-4}	3.7×10^{-5}	0.48
TD-92(1.0)	0.004	0.002	3.2×10^{-4}	0.093
TD-92(1.5)	0.002	7.1×10^{-4}	1.3×10^{-4}	0.037
AGN-95J	6.1×10^{-4}	1.1×10^{-4}	4.7×10^{-6}	0.060
WB	1.1×10^{-4}	2.0×10^{-5}	8.4×10^{-7}	0.011
TD-96	4.7×10^{-8}	4.8×10^{-9}	8.3×10^{-11}	9.0×10^{-6}

[a] $E_\nu > 1.0$ EeV
[b] $E_\nu > 10$ EeV
[c] $E_\nu > 100$ EeV
[d] Two FD's with $\alpha = 60^o$ and 90% efficiency for energies 0.5 EeV $< E_\nu <$ 5 EeV.

V. BACKGROUND EVENTS

We consider here the possibility for a particle of the cosmic radiation to masquerade a DB event depending on the accuracy of the detector. The probability for a proton, for example, to generate two EAS's and masquerade the DB generated by a neutrino depends on two possibilities: 1) that the primary proton interaction generates some fragment that will give rise to a secondary shower deep in the atmosphere with energy higher then the first. 2) that another shower created by some independent particle interacts deep in the atmosphere masquerading the second EAS of the DB.

In the possibility 1, the second EAS will be created by the decay or interaction of the fragment deep in the atmosphere. Usually the primary proton generating an EAS looses roughly half of its energy to the secondary particles that constitute the EAS and therefore it is very hard that a possible second EAS has more energy than the first one. There may

be some cases where the proton looses only a few amount of its initial energy and that a fragment of the EAS created by the proton decays or interacts creating a second EAS with energy higher than the first one. It could generate a background for DB events and it has to be more carefully studied. Now, considering that for energies of the order 1 EeV we have a cosmic ray flux of less than 1 particle per km^2 per year and that the only particles that could probably interact deep in the atmosphere are neutrinos, generating the second independent EAS near the detector, the chance that the primary particle and this second independent neutrino come from the same solid angle direction, in the same kilometer squared, interacting in a time interval of the tau mean life time in the laboratory frame of $\gamma t_\tau \approx 131 \times \frac{E_\tau}{[\mathrm{EeV}]}$ μs is approximately 1 in 10^7, what exclude the possibility 2. The direction of the two EAS's can be identified specially if two FD's trigger the same DB event (with only one detector, it must be difficult to know the direction of the EAS in the plane that contains the EAS and the detector).

Based on this assumptions, E_2/E_1 may be a good parameter to identify DB events if the measured energies from the two EAS's are accurate enough. The error in the energy measured by a FD depends mainly on the atmospheric conditions but hardly will exceed 50%. For a DB event the situation is optimistic because the most important is the relation between the energies of the two EAS and this error is smaller than the error of the absolute energy of an ordinary EAS. We can make a conservative estimation of the error in the average ratio E_2/E_1 considering the error in the absolute energy of 50%. This will give a relative error to the energy ratio of 70%. So, since in average $E_2/E_1 \approx 2.67$ as deduced in Section II, then considering such an error we find 95% of the events such that the energy ratio $E_2/E_1 > 1$. Then $E_2/E_1 > 1$ could be one minimal condition to identify DB events.

Because of the mean life time of the tau, we believe that it is probable that relatively low energy DB will be superimposed looking like an ordinary EAS, i.e., a single EAS generated by a proton. If one detects an ordinary EAS profile of relatively high energy ($E_{EAS} > 10$ EeV), that cannot be considered a DB event with ordinary EAS profile because at such high energies the tau decay length would separate the two EAS's of a DB Phenomenon. For relatively low energies ($E_{EAS} \sim 0.1$ EeV) it must be considered the possibility of a DB event with an ordinary EAS profile and it has to be more detailed studied.

VI. CONCLUSION

Taking into consideration neutrino oscillations, one expects that one third of the high-energy neutrino flux arriving at the Earth should be composed of ν_τ. These neutrinos can interact in the Earth's atmosphere generating a DB event. Many recent works [19, 28, 29, 30, 31] have studied the potential of the Pierre Auger Observatory to detect almost horizontal air showers generated by UHE neutrinos. Here we phenomenologically investigate the potential of a Pierre Auger-like FD to observe DB events.

To calculate the DB event rate we considered different models and limits of UHE neutrino flux in the case of full mixing oscillations and the cross section for charged current interactions only. We computed the amount of matter the neutrino and the subsequent EAS's have to cross in the atmosphere which depends on the incident angle of the neutrino and on tau properties as its decay length when it carries 80% of the incident neutrino energy and its hadronic branching ratio. The neutrino interaction point depth was considered to be within two extreme points where the DB Phenomenon could be detectable. We also considered the detector geometry and trigger configuration when we computed the field of view of the detector and the efficiency depending on the energy and distance. We have not considered the energy dependence of the distance where the efficiency is maximal.

DB events have very particular characteristics. Different from the neutrino events in surface detectors, DB events do not need to come from the very near-horizontal angles. Despite the low probability of interacting at the top of the atmosphere, we can also have ν_τ creating DB events with incident angles of approximately 60^o or larger. DB events also can have a lower primary neutrino energy, around 1 EeV, different from the energies around 50 EeV and beyond expected for an ordinary EAS generated by the highest energy cosmic rays.

Some authors [26, 27] predict limits for the UHE neutrinos that give very few DB events in a Pierre Auger-like FD. This is because the energy range where the DB can be detected is very strict. For EAS energies less then 0.3 EeV the efficiency of the FD detectors may be too low and for ν_τ energies greater then 20 EeV the two EAS's are too separated. In the ν_τ energy range between approximately 2 EeV and 10 EeV a considerable part of the two EAS's that characterize a DB may be detected by the FD's and then we could have a DB trigger. Monte Carlo simulations with tau and ν_τ must be made to study better some aspects as possible

background events and the expected features of this kind of phenomenon, accounting, for example, for fluctuations in the EAS maximum that would make the observation of DB events even more difficult.

Despite the fact the DB Phenomenon may be very rare, it is very important to be prepared for its possible detection, specially in case the Pierre Auger ground array detect near-horizontal air showers which can indicate a sign for electron and/or muon neutrinos. Consequently oscillations imply a considerable number of ν_τ too. With such a motivation, the Auger Observatory trigger could be calibrated to be more sensitive for energies around 1 EeV. With good efficiency in this energy range, more detectors and more years collecting data we could have more significant statistics. In Table I, we presented numbers of DB event rate per year expected for a Pierre Auger-like FD and also for an optimistic hypothetical case with 2 FD's, $\alpha = 60^o$[32] (see Fig. 1) and 90% efficiency for neutrino energies between 0.5 and 5 EeV. For the Pierre Auger-like efficiency case, only the topological defect model TD-92(0) predicts a significant number of DB events, of 1.83 per year for neutrino energy bigger than 1 EeV. On the other hand, assuming the very feasible configuration with 2 FD's and 90% efficiency for neutrino energies between 0.5 and 5 EeV, models like TD-92(0), TD-92(0.5) and also MPR limit can be tested predicting, respectively, 118, 1.46 and 0.48 events per year.

The potential of the DB Phenomenon to acquire valuable information both in particle and astrophysics is irrefutable. For instance, the cross section and flux of the ultra-high energy neutrinos are speculative and can be investigated with DB events.

Acknowledgments

We thank Carlos Escobar, Vitor de Souza, Henrique Barbosa, Walter Mello, Ricardo Sato, Gennaro Miele, Ofelia Pisanti, Dmitry Semikoz and Guenter Sigl for valuable help and comments on the present work. This research was partially supported by "Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq", the European Union Programme of High Level Scholarships for Latin America - Programme Alβan, scholarship no. E04D044701BR, the Spanish grant BFM2002-00345 and "Fundação de Amparo à Pesquisa

do Estado de São Paulo - FAPESP”

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[1] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966).

[2] G. T. Zatsepin and V. A. Kuz'min, JETP Letters **4**, 78 (1966).

[3] F. Halzen and D. Saltzberg, Phys. Rev. Lett. **81**, 4305 (1998).

[4] F. Halzen, *Lectures on neutrino astronomy: Theory and experiment*, Lectures presented at the TASI School (1998), astro-ph/9810368.

[5] J. G. Learned and S. Pakvasa, Astropart. Phys. **3**, 267 (1995).

[6] P. C. Holanda and A. Y. Smirnov, Phys. Rev. D **66**, 113005 (2002).

[7] G. L. Fogli, E. Lisi, and A. Marrone, Phys.Rev. D **64**, 093005 (2001), hep-ph/0105139.

[8] K. Eguchi et al., Phys. Rev. Lett. **90**, 021802 (2003).

[9] S. H. Ahn et al., Phys. Lett. B **511**, 178 (2001).

[10] S. H. Ahn et al., Phys. Rev. Lett. **90**, 041801 (2003).

[11] C. Athanassopoulos et al., Phys. Rev. Lett. **75**, 2650 (1995).

[12] A. Bazarko, in *Proceedings of the 31st International Conference on High Energy Physcis (ICHEP02)* (Amsterdam, 2002), hep-ex/0210020.

[13] S. Eidelman et al., Phys. Lett. B **592**, 251 (2004), pdg.

[14] *Pierre auger project design report* (1997), http://www.auger.org/admin/DesignReport/index.html.

[15] A. Jain et al., Int. J. Mod. Phys. **A17**, 533 (2002), hep-ph/0011310 v2.

[16] M. Ambrosio et al., Tech. Rep. GAP-2003-013, Auger Colaboration (2003), http://www.auger.org/admin-cgi-bin/woda/gap_notes.pl/, astro-ph/0302602.

[17] C. Quigg, M. H. Reno, and T. P. Walker, Phys. Rev. Lett. **57**, 774 (1986).

[18] S. Eidelman et al., Phys. Lett. B **592**, 414 (2004), pdg.

[19] X. Bertou et al., Astropart. Phys. **17**, 183 (2002), astro-ph/0104452.

[20] A. Kusenko and T. Weiler, Phys.Rev.Lett. **88**, 161101 (2002), hep-ph/0106071 v2.

[21] R. Gandhi, C. Quigg, M. H. Reno, and I. Sarcevic, Phys. Rev. D **58**, 093009 (1998).

[22] J. A. Bellido, Tech. Rep. GAP-98-027, Auger Colaboration (1998), http://www.auger.org/admin-cgi-bin/woda/gap_notes.pl/.

[23] P. Bhattacharjee, C. T. Hill, and D. N. Schramm, Phys. Rev. Lett. **69**, 567 (1992).

[24] G. Sigl, Space Science Reviews. **75**, 375 (1996).

[25] K. Mannheim, Astropart. Phys. **3**, 295 (1995).

[26] J. Bahcall and E. Waxman, Phys. Rev. D **64**, 023002 (2001), hep-ph/9902383 v2.

[27] J. P. Rachen, R. J. Protheroe, and K. Mannheim, Phys. Rev. D **63**, 023003 (2001), astro-ph/9812398 v3.

[28] K. S. Capelle et al., Astropart. Phys. **3**, 321 (1998), astro-ph/9801313.

[29] H. Wilczyński, Tech. Rep. GAP-00-020, Auger Colaboration (2000), http://www.auger.org/admin-cgi-bin/woda/gap_notes.pl/.

[30] M. Ave et al., Astropart. Phys. **14**, 109 (2000), astro-ph/0003011.

[31] C. Aramo et al., Astropart. Phys. **23**, 65 (2005), astro-ph/0407638.

[32] The possibility of increasing the overture of FD in Pierre Auger Observatory is presently under consideration in the collaboration.